Numerical studies on impact tests of a full-size metal storage cask

N. Kageyama & K. Shirai
Civil Engineering Research Laboratory,
Central Research Institute of Electric Power Industry, Japan

Abstract

The necessity of the interim dry storage of nuclear spent fuel using metal casks has risen year by year. Metal gaskets have been used worldwide to prevent leaks from the metal cask during long-term storage. There are still uncertainties for the impact behaviours of the metal cask without impact limiters under severe impact loads, such as drop or tipping-over events in the interim storage facility. Therefore, it is very important to clarify the dynamic behaviour of the metallic gaskets subjected to sliding and opening movements of the lid structures during impact loads.

To demonstrate the structural integrity and leak-tightness of gasketed joints of the metal cask against drop impacts, many impact tests and analysis have been performed based on transport regulations or storage accident scenarios. The inert gas will be released instantaneously under very slightly opening or sliding movements of the lid structures. Until now, there has been less evaluation data concerning the instantaneous leak rates from the lid gasket during impact loading.

Therefore, two impact tests with the full-size metal cask (horizontal drop and rotational impact onto concrete floor) have been executed and the relationships between gasket movements and the leak rate of inert gas have been clarified. Moreover, according to the drop analysis using dynamic analysis code LS-DYNA and the comparison with the experimental results, the impact behaviour of the complicated gasketed joints can be simulated accurately and directly.
Keywords: interim dry storage, metal storage cask, lid gasket and LS-DYNA.

WIT Transactions on The Built Environment, Vol 87,
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/SU060391

1 Introduction

As the demand for electricity grows, the amount of spent fuel discharged from nuclear power plants has increased. Therefore, the need for interim dry storage has risen year by year. For interim dry storage, the metal cask with the metallic lid gasket have been used worldwide to keep high leak-tightness for long-term storage.

Generally, leak-tightness of metallic gasket joints is very sensitive to \sliding and opening movements by external impact load. However, there are still uncertainties for the impact behaviours of the metal cask without impact limiters under severe impact loads, such as drop or tipping-over events in interim storage facility. Therefore, it is very important to clarify the dynamic behaviour of the metallic gaskets subjected to sliding and opening movements of the lid structures during impact loads.

In this study, two drop tests, a horizontal drop test and a rotational impact test, were performed using full-size metal cask model [1]. In these tests, sliding and opening movements of lids are measured in detail.

The next step, in order to establish an evaluation method of the behaviour of the lid structure during impact load, post-analysis for drop tests was performed using dynamic analysis code LS-DYNA.

2 Impact test with the full-size metal cask onto concrete floor

In order to measuring movements of the lid structure of metal cask during the impact load, two impact tests of the full-size metal cask were performed. The metal cask without impact limiters was dropped onto the concrete floor, which simulates the floor of an interim dry storage facility.

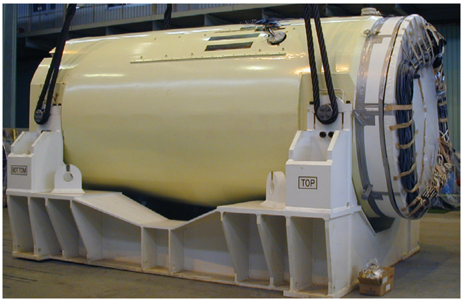

Figure 1: Overview of full-size metal cask model.

2.1 Full-size metal cask model

Figure 1 shows an overview of the full-size metal cask model for impact tests, and Table 1 shows the main specifications of this model. This model has been designed as metal cask for dry storage and transportation of 21 PWR-type fuel assemblies.

This cask has a double lid structure and lid gaskets are double type metal gasket made of aluminium coating material. For primary and secondary lids, a section diameter of the gasket is 5.6 mm and 10 mm, respectively.

This cask has a gap between the lid side and body. At initial conditions, primary and secondary lids are set carefully to make the gap equal. A nominal gap of primary and secondary lids at one side is 1mm and 0.5 mm, respectively.

Table 1: Specification of metal cask model.

Part	Material	Size (mm)	Weight (ton)
Body	Carbon steel (ASTM A350LF5)	Internal Dir.: 1672 Thickness: 250	84.6
Neutron Shielding	Lightweight concrete equivalent to resin	Thickness: 164	
Outer Shell	Carbon steel	Outer Dir.: 2524 Thickness: 12	
Trunnion	Stainless steel (SUS F630)	Diameter: 190	
Primary Lid	Carbon steel (ASTM A350LF5)	Outer Dir.: 1946 Thickness: 198	4.2
Secondary Lid	Carbon steel (ASTM A350LF5)	Outer Dir.: 2236 Thickness: 235.5	5.5
Basket and Contents	Equivalent weight		3.5+21.2
Total Weight			119

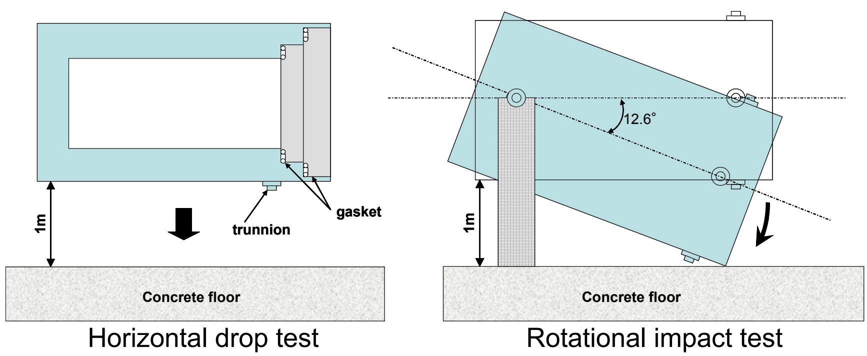

Figure 2: Impact tests condition.

2.2 Impact test condition

Figure 2 shows the metal cask's position in the two impact tests, horizontal drop test and rotational impact test.

The first test is free drop from 1m in a horizontal orientation. This condition simulates the drop accident during a horizontal handing at an interim dry facility. Horizontal handling operations in such facility are actually performed with impact limiters.

In the second test, considering an accident during operation of changing from horizontal position to vertical position, the direct collision with lid structure of the cask to the floor is considered by rotational impact load. The rotational center of the cask is set to the trunnion attached to the bottom sides.

2.3 Measurement

Table 2 shows main items of measurement for the impact tests.

The important factors in this measurement are as follows;

- To measure the instantaneous leak, the helium leak rate from lid gaskets is measured continuously during impact.
- Sliding or opening movements of the lid structure are measured precisely and continuously with inductive displacement sensors.

Table 2: Measurement items.

Items	Part	Measuring point
Acceleration	Main body	Axial center (0° and 180° side)
	Primary lid	Center
	Secondary lid	Center
	Contents	Axial center (180° side)
Displacement	Primary lid sliding	0°, 45°, 90°, 135°, 180° and 270° side
	Primary lid opening	0°, 45°, 90°, 135° and 180° side
	Secondary lid sliding	0°, 45°, 90°, 135°, 180° and 270° side
	Secondary lid opening	0°, 45°, 90°, 135° and 180° side
Bolt stress	Secondary lid bolt	0°, 60°, 120°, 180°, 240° and 300° side
Leak rate	Primary lid gasket	
	Secondary lid gasket	

Note: 0-180° direction of the metal cask is drop direction (0° is lower side).

2.4 Impact test result

Tables 3 and 4 show summary of horizontal drop and rotational impact test results.

Maximum leak rates during two impact tests were lower than 1×10^{-8} Pa m^3/s. Therefore, it is demonstrated that the integrity of the leak-tightness of the metal cask with the gasketed joints has been verified during impact loads.

And detail movements of lid structure are described in the next chapter as a comparison of the analysis result.

Table 3: Summary of horizontal drop test result.

Acceleration	Main body	Max. 50 G
	Primary lid	Max. 16 G
Primary lid movement	Sliding	Max. 0.4 mm
	Opening	No significant change
Secondary lid movement	Sliding	Max. 0.3 mm
	Opening	No significant change
	Axial stress of bolt	No significant change
Maximum leak rate	Primary lid gasket	2.38×10^{-10} Pa m^3/s
	Secondary lid gasket	2.85×10^{-9} Pa m^3/s

Table 4: Summary of rotational impact test result.

Acceleration	Main body	Max. 16 G
	Primary lid	Max. 48 G
Primary lid movement	Sliding	Max. 0.6 mm
	Opening	Max. 0.11 mm
Secondary lid movement	Sliding	Max. 1mm at 0° side Max. 0.6mm at 45° side
	Opening	No significant change
	Axial stress of bolt	50 MPa increase
Maximum leak rate	Primary lid gasket	3.86×10^{-9} Pa m^3/s
	Secondary lid gasket	8.37×10^{-9} Pa m^3/s

3 Analysis of the impact test

To confirm the accuracy of the numerical analysis of the lid structure behaviour during impact load, the analysis of the impact tests have been executed with dynamic analysis code LS-DYNA.

3.1 Analysis model

The analysis code is LS-DYNA Ver.970 with user subroutine of material model for concrete originally developed by CRIEPI [2].

Figure 5 shows analysis model of horizontal drop test. This model is made as a 1/2 symmetric model considering the cask structure and the drop orientation. Table 5 shows a number of elements and nodes of this model.

3.1.1 Material properties

In this analysis model, metallic materials are used for body, lid, lid bolts, outer shell, trunnion, contents and the reinforcement bars in the concrete floor. These materials are simulated as isotopic elastic plastic material. Table 6 shows material properties applied to the calculation.

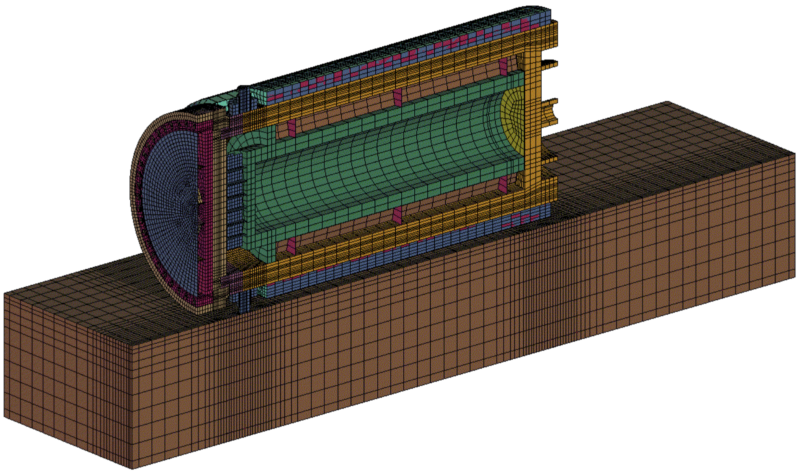

Figure 3: Analysis model of horizontal drop test.

Table 5: Outline of analysis model.

Part	Elements	Nodes
Main body	91210	80221
Primary and secondary lid	22146	15164
Contents	3776	3104
Concrete floor	28800	29658
Total	145932	128147

Table 6: Material properties of metallic materials.

Part	Density (kg/m^3)	Young's modulus (MPa)	Poison's ratio	Yield stress (MPa)	Hardening modulus	Strain rate parameter*	
						P	C
Body and lid	$7.85x10^3$	203460	0.3	205	2034	200	5
Lid bolts	$7.85x10^3$	202000	0.3	890	2020	200	5
Outer shell	$7.86x10^3$	203000	0.285	215	2030		
Trunnion	$7.86x10^3$	195000	0.3	725	1950	200	5
Contents	$7.86x10^3$	203000	0.3	215	2030		
Reinforced bar	$7.86x10^3$	206000	0.3	295	2060		

*Note: Yield stress coefficient at strain rate $\dot{\varepsilon} = 1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/P}$.

In this analysis model, concrete materials are used for the concrete floor and lightweight concrete filled between main body and outer shell. Table 7 shows the material properties of these concrete materials. These properties have been determined from the results of material tests. Test Samples are prepared from the actual test model's concrete by a core boring method. These values are used for input data of user subroutine of concrete material.

Table 7: Material properties of concrete.

Part	Density (kg/m^3)	Shear modulus (MPa)	Bulk modulus (MPa)	Compressive strength (MPa)	Tensile strength (MPa)
Concrete floor for horizontal drop	2.286x10^3	11939	16177	36.92	3.30
Concrete floor for rotational impact	2.281x10^3	11919	15706	35.93	2.39
Lightweight concrete	1.543x10^3	5876	8805	22.68	3.30

3.2 Analytical condition

3.2.1 Contact condition

On every contact surface between parts of this analysis model, a slide surface condition with voids is applied. A friction coefficient of the slide surface is set to 0.14. However, only for the flange surface of primary and secondary lid, this coefficient is set to an experimental value (0.6) obtained from the sliding test result with a scaled lid model.

3.2.2 Tightening of lid bolts

Initial tightening of the lid bolt is set by the method of relaxation of initial penetration. This initial tightening stress of lid bolts is equivalent to tightening torque of 2400 N-m.

3.2.3 Initial lid position

In the rotational impact test, it is clear from the analysis of the test result that the initial position of the secondary lid has been shifted from the center by 0.2mm on the 180-degree side (opposite side of drop). Therefore, the secondary lid model for rotational impact test is set to such an eccentric position.

3.2.4 Initial condition

These analyses have been executed to verify the accuracy of the calculation model with our original concrete model. Initial condition of two impact tests is shown in Figure 2.

For the horizontal drop test, initial velocity 4430 m/s equivalent to the free drop velocity from a height of 1m is set to the cask model.

For the rotational impact test, initial rotational velocity is 1.09 rad/s equivalent to the velocity from the rotation of falling 1m. The rotational center is set to a center axis of bottom side trunnions.

3.3 Comparison with the test result

Comparison between analysis and test result is summarized as follows especially taking care of lid movements. Maximum values of lid movements of analysis and test results are shown in Table 8.

3.3.1 Horizontal drop analysis

Figure 4 shows the time history of the primary lid's acceleration in the drop direction. The maximum acceleration value is calculated from the slope of velocity near peak of acceleration. They are almost the same for the test result and analytical result.

Figure 5 shows the time history of the primary lid sliding. The maximum amount of sliding is same from the test result and analysis, because the friction coefficient is based on examination. However, the initial slope of sliding is not same. It is expected that it is necessary to clarify the detail of initial dynamic friction coefficient.

3.3.2 Rotational impact analysis

Figure 6 shows the time history of the primary lid's acceleration in the drop direction. It is found that the acceleration values calculated from the slope of velocity are more conservative than those from the drop test condition.

Figure 7 shows the time history of the secondary lid sliding. As to the lid movements, it seems that there is a good agreement between test values and calculation results by applying the experimentally obtained friction coefficient value and initial lid position. However, as shown in Table 8, the accuracy of very small opening of lids is not as good as the accuracy of the lid slide.

Table 8: Summary of comparison with test result.

Items		Horizontal drop test		Rotational impact test	
		Test	Analysis	Test	Analysis
Acceleration	Primary lid	Max. 16G	Max. 17G	Max. 48G	Max. 40G
Primary lid	Sliding	0.4 mm	0.4 mm	0.6 mm	0.7 mm
	Opening	---	---	0.11 mm	0.01 mm
Secondary lid	Sliding	0.3 mm	0.2 mm	0.6 mm	0.4 mm
	Opening	---	0.02 mm	0.01 mm	0.05 mm

--- : No significant change.

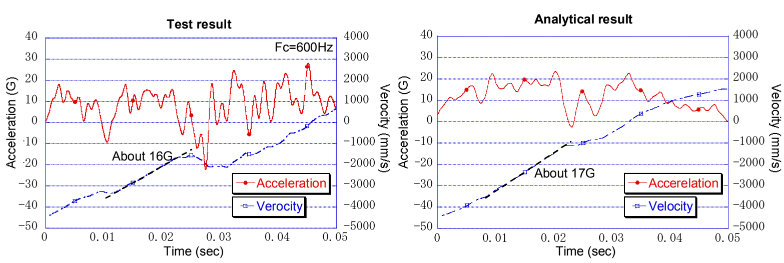

Figure 4: Time history of primary lid's acceleration.

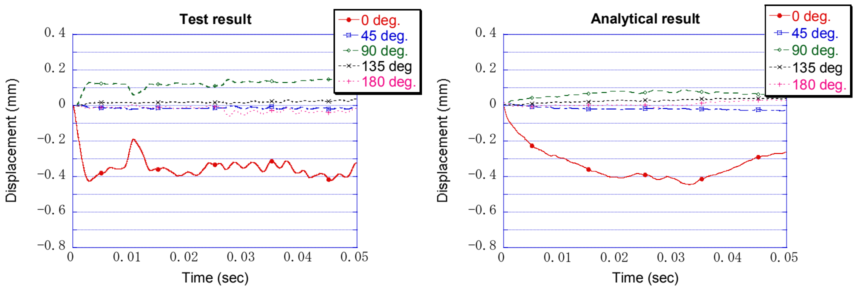

Figure 5: Time history of primary lid's slide.

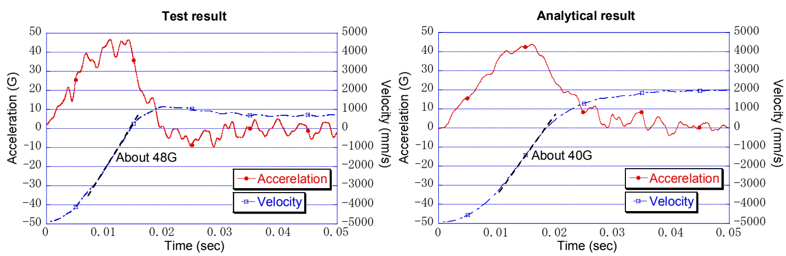

Figure 6: Time history of primary lid's acceleration.

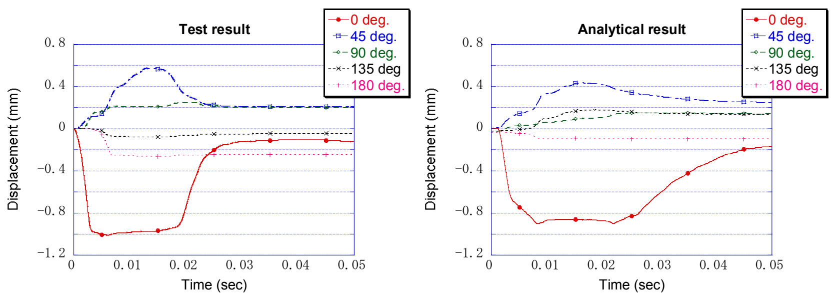

Figure 7: Time history of secondary lid's slide.

4 Conclusion

Two drop tests, a horizontal drop test and a rotational impact test, were performed using full-size metal cask model. During these drop tests, primary and secondary lid movement were observed in detail, and maximum leak rates from lid were lower than 1x10^{-8} Pa m^3/s.

Post-analyses for drop tests were performed, and with regards to the lid movement there was a good agreement between test values and calculated results by taking care of the friction coefficient and the initial position of lid.

Acknowledgment

This work has been carried out under the contract from Ministry of Economy, Trade and Industry.

References

[1] H. Takeda, et al, Leakage Evaluation of Metal Cask during Drop Test, *Proc. of the GLOBAL 2005*, Tsukuba Japan, 2005.
[2] K. Shirai, et al., *Impact Analysis of Reinforced Concrete Structure by Finite Element Method*, Abiko Research Laboratory Rep. No. U93053, CRIEPI, Japan, 1993.